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Advanced Engineering Systems

An Engineering System for Automated Design and Optimization of Fuel Cell-Powered Vehicles

American Society of Mechanical Engineers
First International Conference on
Fuel Cell Science, Engineering and Technology
Rochester, NY, April 21-23, 2003

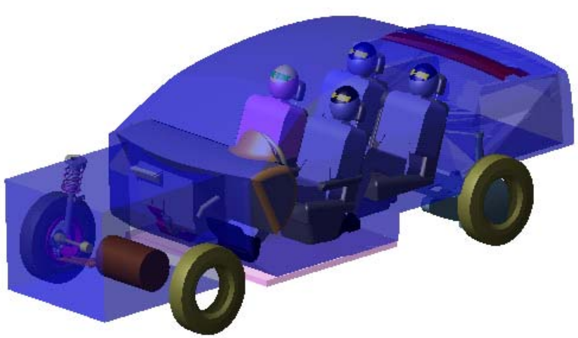
Background

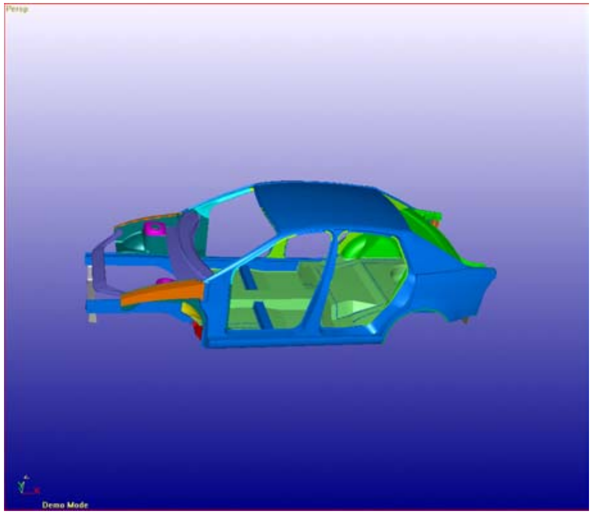
- In 2002, the National Renewable Energy Laboratory contracted VulcanWorks to provide an Advanced Engineering Environment (AEE) configured for development of automotive vehicles powered by fuel cell/fuel processor systems
- The Vulcanworks AEE product is an integrated set of tools, tailored to solve design problems in specific environments and processes.
- The AEE allows extremely rapid iteration of system designs, with automated analysis capability.
- It contains a database of design and manufacturing rules, an automated geometry creation engine, links to a variety of CAE analysis packages, and a Web-browser interface.

Current Design Processes Automated with AEE

The AEE framework has been used for design automation of the following systems

- Automotive Body Structure
- Automotive Suspension
- City Bus Suspension
- Heat Treat Furnace
- Plastic Injection Molding Manifold
- Fuel Cell Powered Vehicle (prototype)





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AEE for Advanced Propulsion

Rationale for Development

- Suppliers of advanced propulsion systems need vehicle-level design guidance in order to meet requirements for commercially viable products
- OEM's are the ultimate authority on vehicle integration, and provide some level of this guidance, but their time is limited to interact with suppliers' trade-off studies
- An integrated analytical design process was desired that simultaneously evaluates effects of design proposals on efficiency, package, safety, dynamics, NVH, comfort, etc.

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Rationale for Development (continued)

- The AEE for fuel-cell powered vehicles will provide DOE and the manufacturers and developers of advanced fuel cell technology an understanding of how their technical targets and design decisions impact the performance of systems and vehicles in various vehicle segments
- Fuel cell-vehicle design tradeoffs will benefit significantly from design automation and mathematical optimization
- The AEE forms the base around which optimization routines can be applied to manage complex fuel cell/reformer design tradeoffs

AEE for Advanced Propulsion
Phase I Project Description

- Project Timeline: May through October 2002
- Project objectives
  - Create the AEE design for fuel cell/reformer systems and fuel cell powered vehicles
  - Prove the viability of the design by development of a functioning AEE prototype that is capable of performing a representative design task
  - Use the AEE prototype to demonstrate various design decisions and trade-offs available from the fully-developed AEE
- Phase 2 (proposed) complete development of the AEE design

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Phase I Project Results – AEE Design

- AEE design completed and documented
- Design capabilities include
  - Design tradeoffs in the fuel cell and reformer
  - Integration with systems to develop vehicle package alternatives, structure, and suspension designs
  - Optimized packaging of fuel cell/reformer components in the vehicle
  - Integration of analyses to predict performance of the vehicle
    - Energy efficiency
    - Performance (gradeability, acceleration, load capacity, top speed, range)
    - Vehicle accessory capacity (air-conditioning, heated backlight, etc.)
    - Stability and cornering capability
    - Safety/crashworthiness
  - Optimization capability spanning all of the above in order to develop optimal designs for different vehicle mission assumptions

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Phase I Project Results – AEE Prototype

- Representative design task is to evaluate the vehicle effects of various startup strategies
  - Vary the percentage of full power available during the first five minutes of cold-start operation
- Prototype has been completed and successfully performs this task
- Prototype includes design rules and geometric models for
  - Fuel cell components
  - Fuel reformer components
  - Vehicle occupants
  - Vehicle interior
  - Vehicle architecture
  - Suspension

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Phase I Project Results – Fuel Cell and Reformer Relationships Developed

- Fuel reformer/burner volume as function of stack output power and operating pressure
- Fuel reformer time to zero CO as function of reformer volume and power extracted from turbine for vehicle propulsion
- Reformate CO concentration as function of time
- Steam generator volume as function of stack output power
- Fuel cell volume as function of stack output power, operating temperature, and operating pressure
- Fuel cell CO tolerance as function of operating temperature
- Fuel cell startup time as function of reformer startup and CO tolerance

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Phase I Project Results – Fuel Cell and Reformer Relationships Developed (continued)

- Condenser volume as function of fuel cell operating temperature, pressure, and output power
- Coolant radiator volume as function of fuel cell operating temperature, pressure, and output power
- Turbo-compressor volume as function of operating pressure
- Number of batteries as function of startup time, drive cycle power and energy profiles, and user choice of power drawn from the turbine for vehicle propulsion
- Traction motor/drive volume as function of peak power

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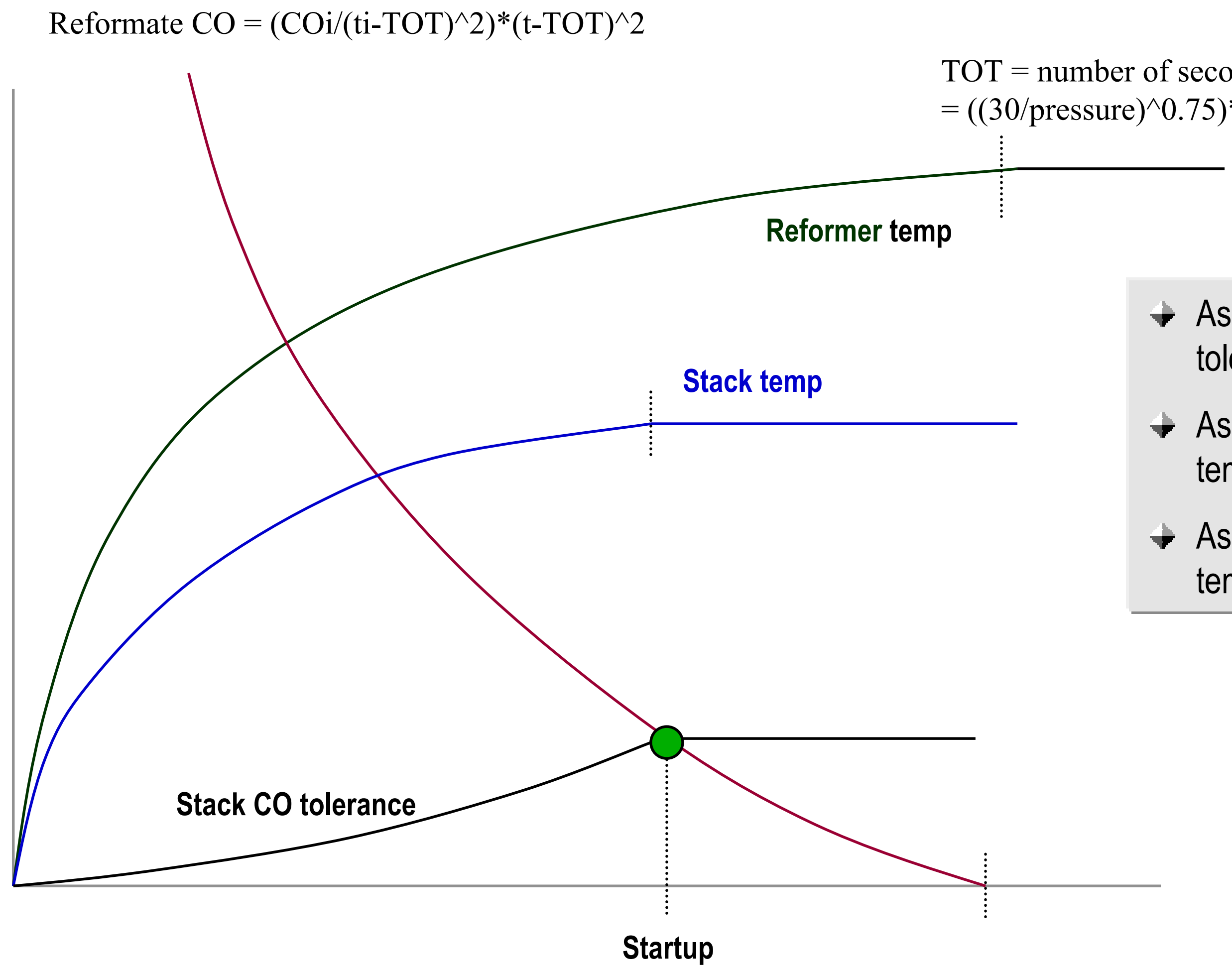
Phase I Project Results – Example Fuel Cell / Reformer Design Relationships



- As stack operating temp up, CO tolerance up
- As system pressure up, reformer temperature rises faster
- As power draw from turbo up, reformer temp rises more slowly

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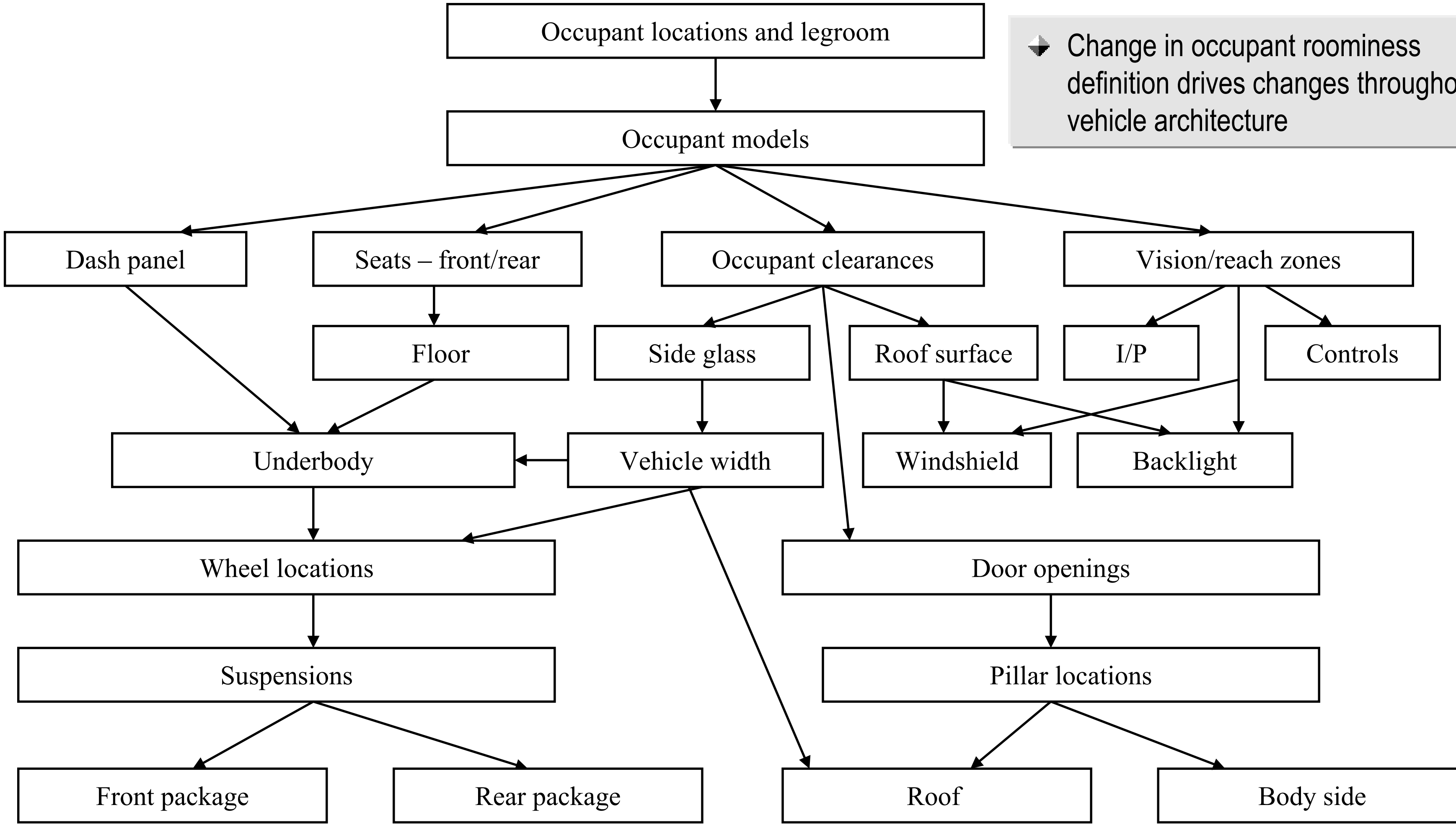
Phase I Project Results – Example Vehicle Relationship



- Change in occupant roominess definition drives changes throughout vehicle architecture

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Phase I Project Results – Prototype

- Prototype contains:
  - Link to ADVISOR (NREL) to compute cycle power and energy
  - Optimization routine to package fuel cell components in the vehicle
  - Alternative design sequences
  - Alternative vehicle architectures
    - Vehicle design fixed
    - Vehicle design adjustable to suit fuel cell size
    - Under-floor package space

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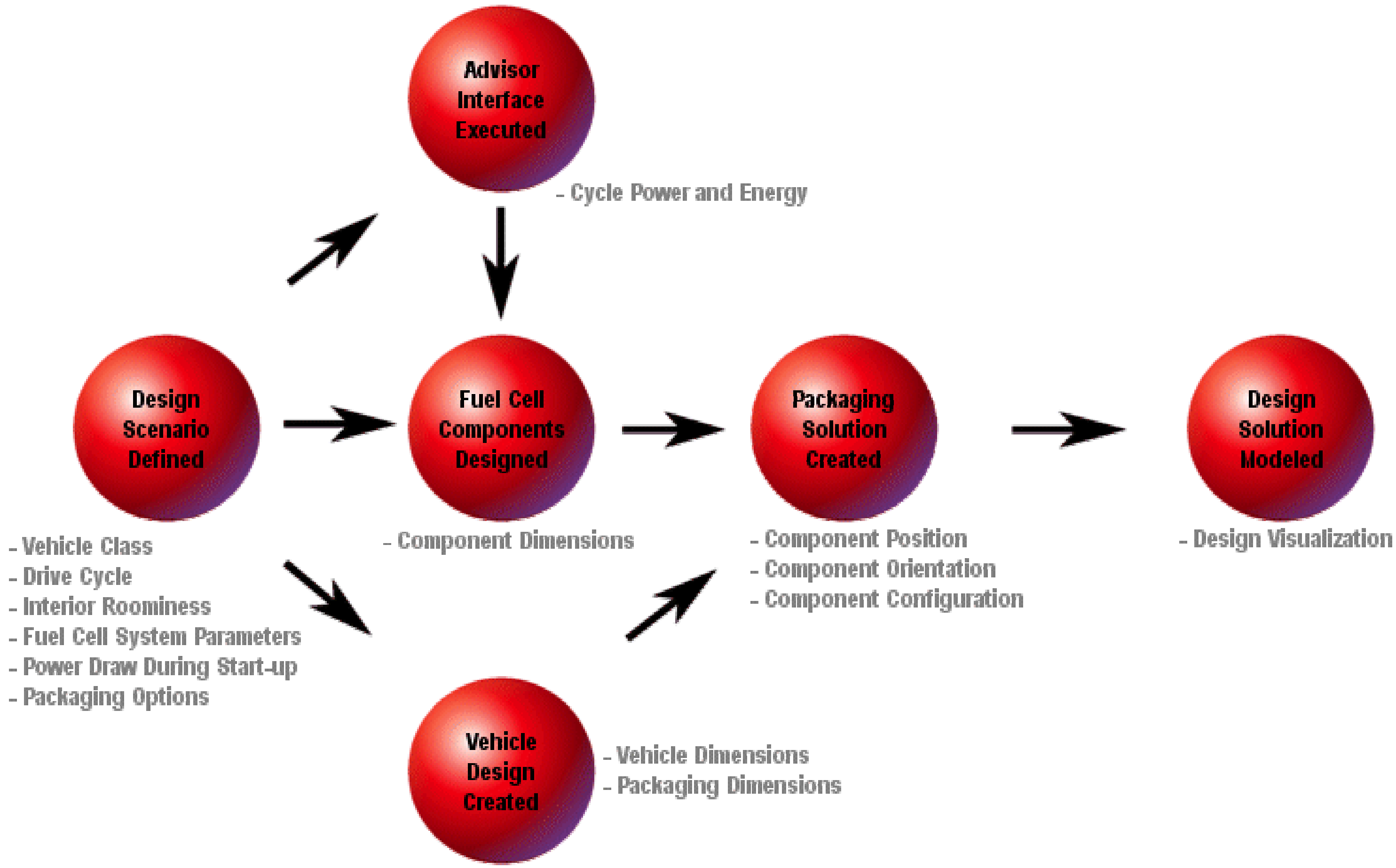
Phase I Project Prototype - Design Process



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Phase I Project Packaging Optimizer – Optimization Design Problem

Design scenario defines geometric requirements of vehicle

- Vehicle architecture dimensions
- Front, rear and under-floor packaging compartment dimensions

Design scenario defines geometric requirements of fuel cell system components

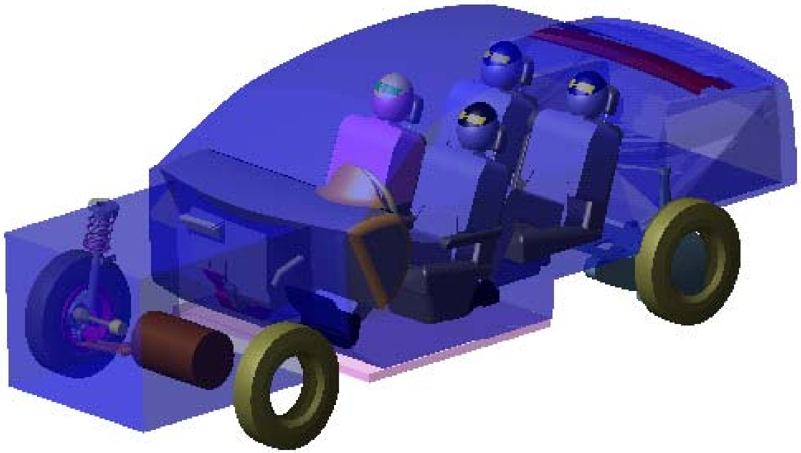
- Component volumes
- Number of batteries

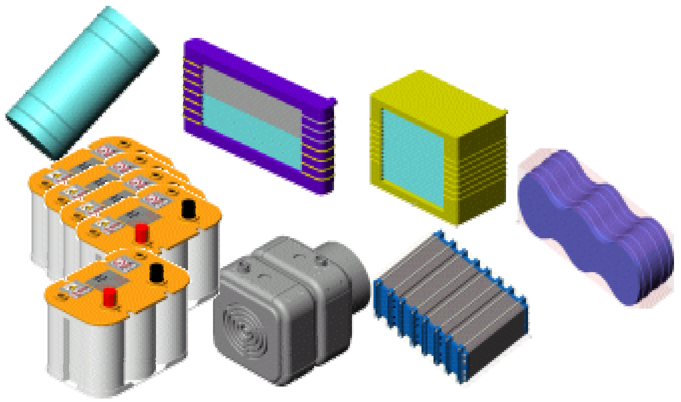
Design rules define valid component orientations and mechanical configurations and relative position constraints

- 3D dimensional options of components for defined volumes (different mechanical design that achieves the same functional requirement)
- Component x can be rotated in 3 dimensions, component y cannot be rotated

Packaging Optimizers attempts to fit system components into available packaging space

- All components must fit into defined packaging space under given constraints





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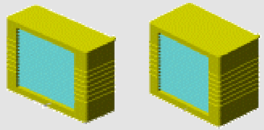
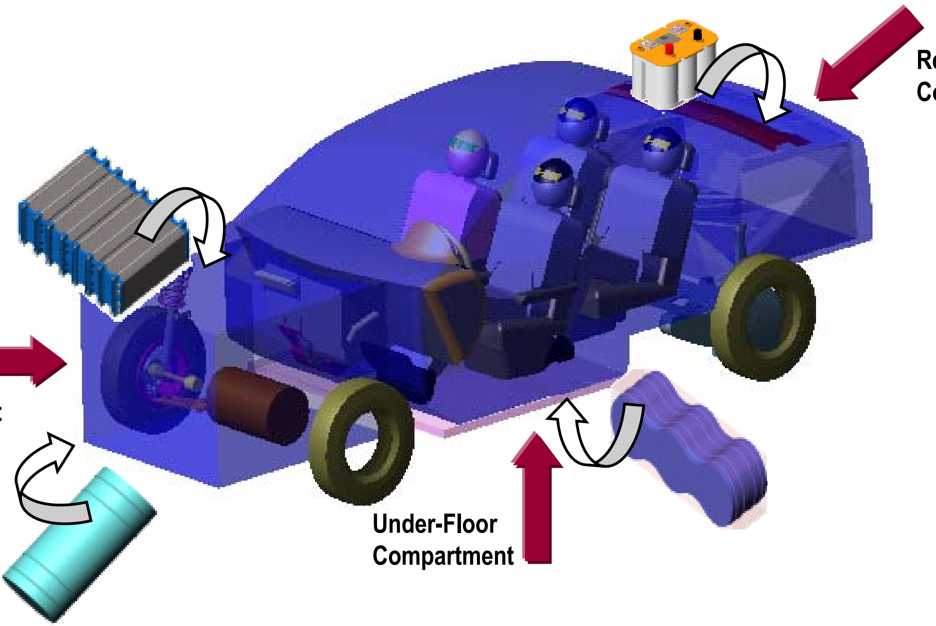
Phase I Project Packaging Optimizer – Optimization Packaging Process

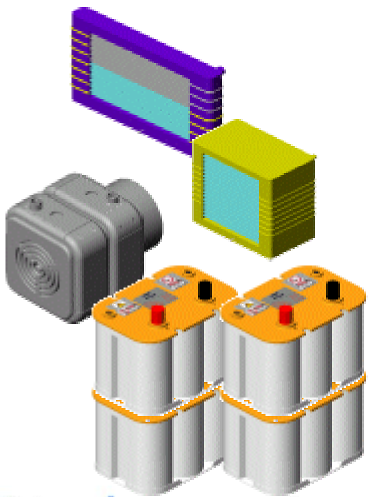
- Components are placed into valid packaging compartments
- Placement must not violate defined constraints
  - Components may not collide
  - Only defined orientations and configurations are allowed
  - Only specified components are allowed in specific compartments (ex. only batteries may be allowed in rear)
- All component permutations are reviewed until a solution is achieved – millions of unique permutations are possible for each design scenario

All valid orientations may be attempted



All valid configurations may be attempted





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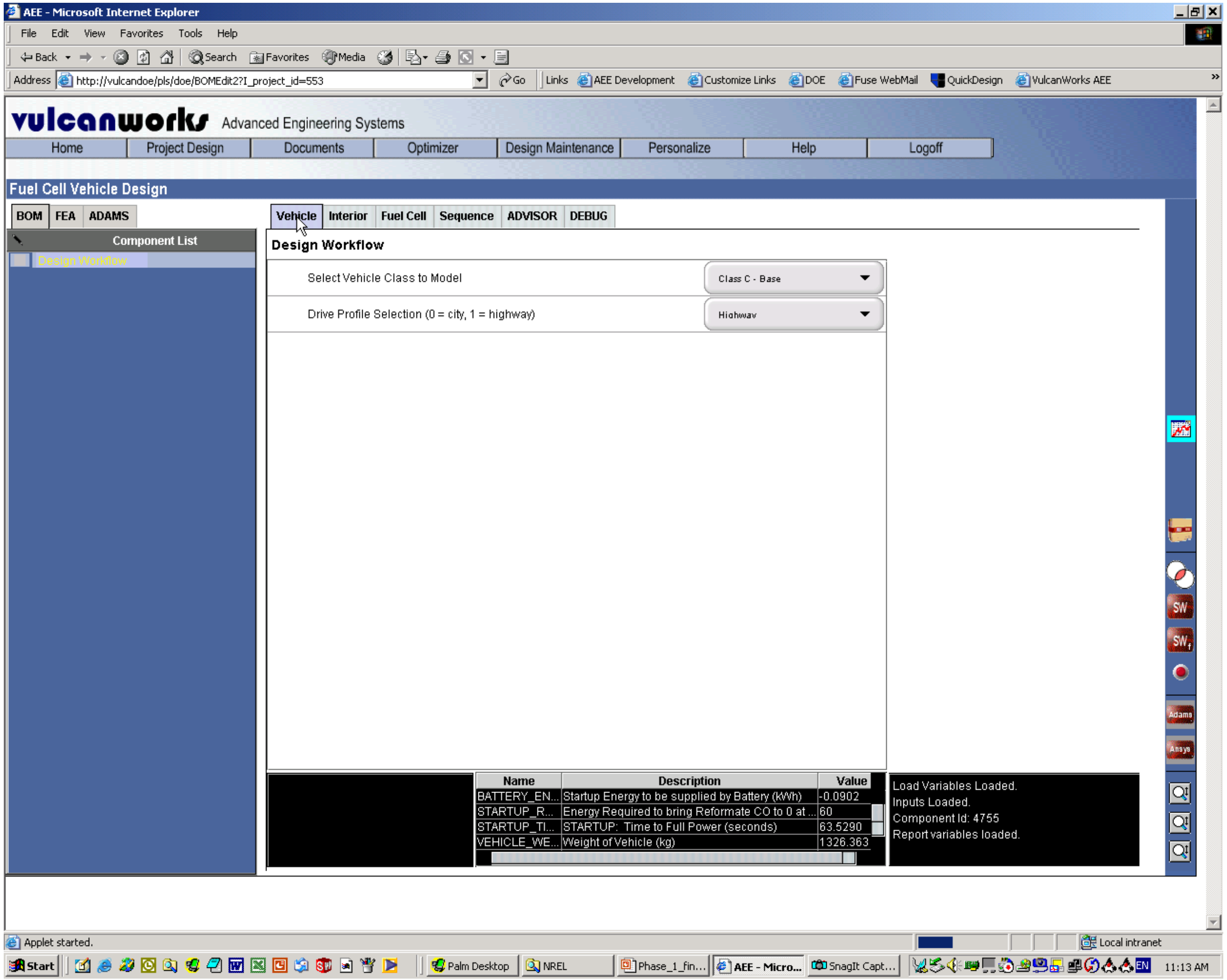
Phase I Project Prototype - User Interface



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Phase I Project Prototype - Design Scenario Definition

Vehicle | Interior | Fuel Cell | Sequence | ADVISOR | DEBUG

Design Workflow

Select Vehicle Class to Model	Class C - Base
Drive Profile Selection (0 = city, 1 = highway)	Highway

Vehicle | Interior | Fuel Cell | Sequence | ADVISOR | DEBUG

Design Workflow

SGRP Rear L50 (x-axis)	773.0
SGRP Rear (z-axis)	300.0
Effective Leg Room	815.0
SGRP Front H30 (z-axis)	297.0

Vehicle | Interior | Fuel Cell | Sequence | ADVISOR | DEBUG

Design Workflow

Operating Temperature (degrees C)	65
Operating Pressure (psia)	30
Fuel Cell Stack Peak Power Requirement (kW)	50.0
STARTUP: Power to be Supplied by Turbo (kW) with Battery Supplement	12.5
STARTUP: Stationary Time Before Drive-away (seconds)	0.0
STARTUP: Use Battery to Supplement Power Requirement	✔

Vehicle | Interior | Fuel Cell | Sequence | ADVISOR | DEBUG

Design Workflow

Design Sequence	Design to Vehicle Package
Check to use Underfloor Architecture	☐
Check to allow Power Electronics Module to be packaged in rear compartme	☐

Vehicle | Interior | Fuel Cell | Sequence | ADVISOR | DEBUG

Design Workflow

Rolling Resistance Coefficient	0.0055
Density of Air	1.2
Gravity (m/s^2)	9.81
Auxiliaries (W)	500.0
Cargo Mass (kg)	136.0

Project user sets up design scenario

- Vehicle Selections
- Occupant Definition
- Fuel Cell Design Parameters
- Packaging Sequence
- ADVISOR Parameters

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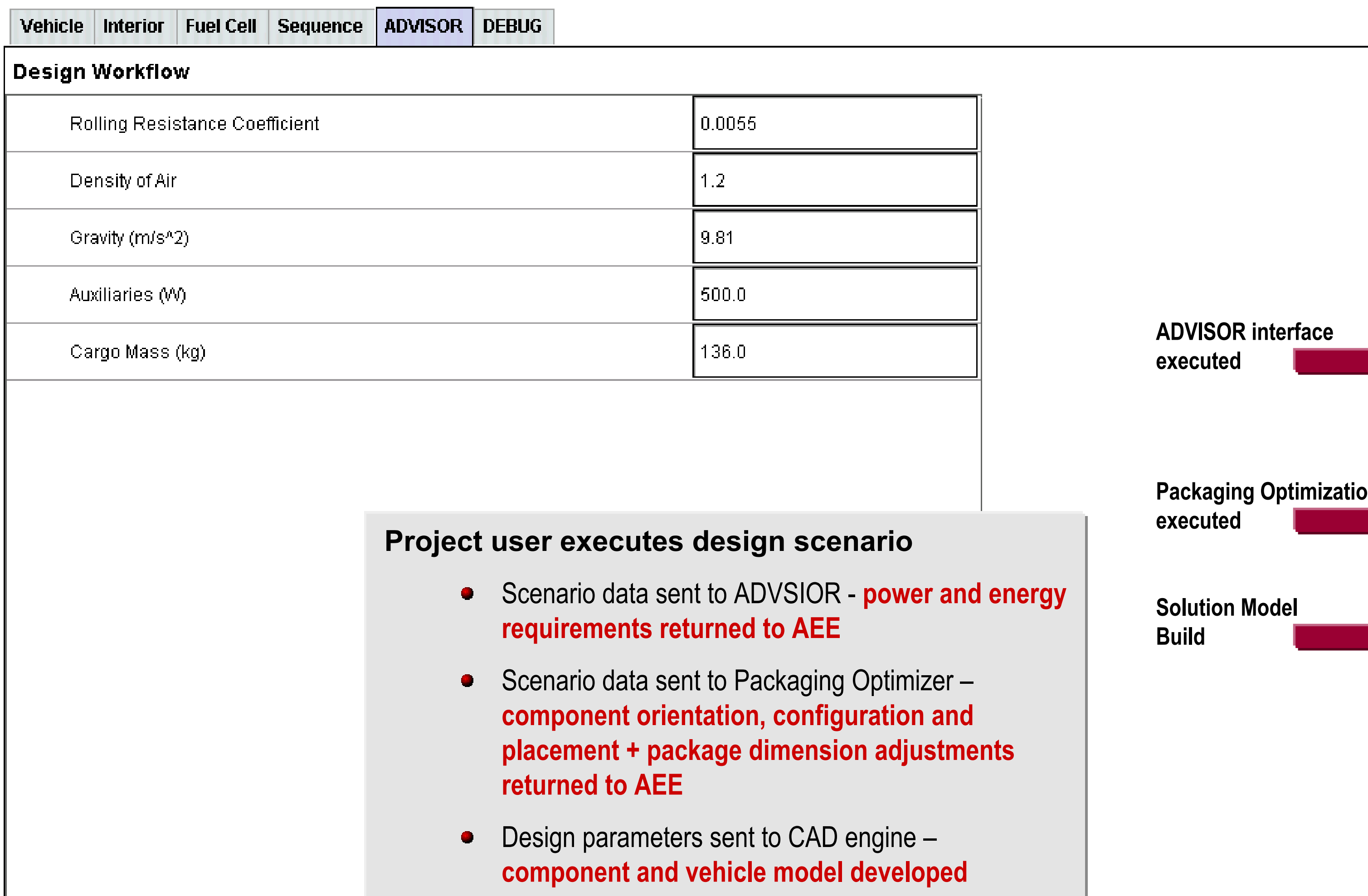
Phase I Project Prototype - Design Scenario Execution



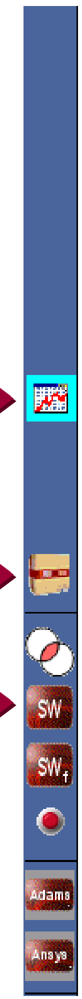
Project user executes design scenario

- Scenario data sent to ADVSIOR - **power and energy requirements returned to AEE**
- Scenario data sent to Packaging Optimizer – **component orientation, configuration and placement + package dimension adjustments returned to AEE**
- Design parameters sent to CAD engine – **component and vehicle model developed**

ADVISOR interface executed

Packaging Optimization executed

Solution Model Build



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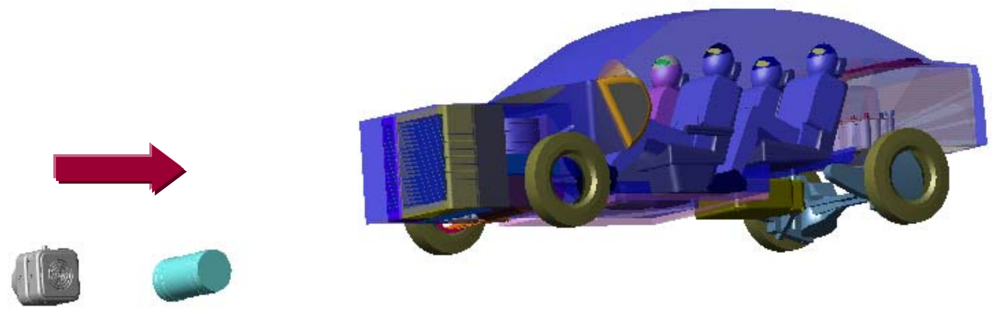
Phase I Project Prototype - Analysis Results Example

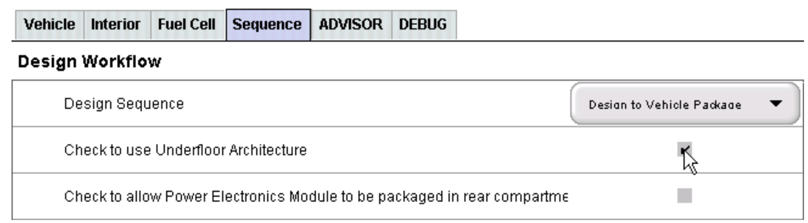
Packaging solution is not achievable with defined scenario parameters

- Turbo compressor and steam generator cannot be packaged



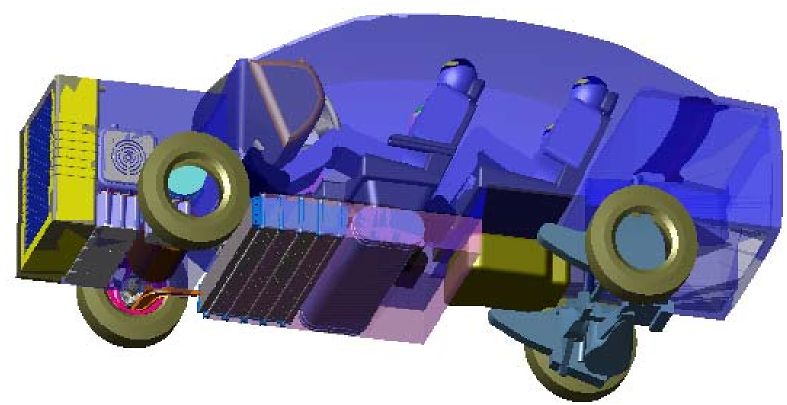
User adjusts scenario definition

- Under-floor packaging is allowed



Packaging solution is achieved

- Vehicle floor is raised to create under-floor packaging compartment
- All components fit into available packaging space
- Fuel cell and fuel reformer are placed in under-floor compartment



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Phase I Project Prototype - Analysis Results Example

The following results are based upon the following design selections

- C-class vehicle
- Highway drive cycle
- 2 sets of Fuel Cell Operating Condition
  - 3 sets of Start-up options for each Operating Condition
    - 3 Packaging Options for each Start-up Option

Stack Temp	Stack Pressure	Vehicle during reformer startup	Package Option	Turbo power draw	Battery Suppl	Time to full stack power	Batteries required	Components Packaged	Width	Height	Length	Weight	Drag Coef
									Vehicle Design Characteristics				
65C	30 psia	stationary	Vehicle	0	no	53.9	0	not turbo	1,710	1,431	4,443	1,326	0.33
			Fuel Cell					all	1,910	1,431	4,643	1,548	0.37
			Under-floor					all	1,710	1,581	4,443	1,465	0.33
65	30	immediate driveaway	Vehicle	12.5	yes	63.5	1	not turbo	1,710	1,431	4,443	1,326	0.33
			Fuel Cell					all	1,910	1,431	4,643	1,548	0.37
			Under-floor					all	1,710	1,581	4,443	1,465	0.33
65	30	immediate driveaway	Vehicle	0	yes	53.9	6	not turbo	1,710	1,431	4,443	1,326	0.33
			Fuel Cell					all	1,910	1,431	4,643	1,548	0.37
			Under-floor					all	1,710	1,581	4,443	1,465	0.33
90	45	stationary	Vehicle	0	no	36.1	0	not steam generator	1,710	1,431	4,443	1,326	0.33
			Fuel Cell					all	1,910	1,431	4,643	1,548	0.37
			Under-floor					all	1,710	1,581	4,443	1,465	0.33
90	45	immediate driveaway	Vehicle	12.5	yes	41.3	1	not steam generator	1,710	1,431	4,443	1,326	0.33
			Fuel Cell					all	1,910	1,431	4,643	1,548	0.37
			Under-floor					all	1,710	1,581	4,443	1,465	0.33
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Phase I Project Results Summary

- Completed the design of AEE for vehicles with advanced propulsion systems
- Proved out the design by completing a prototype AEE
- Exercised the prototype on a representative fuel cell/vehicle design study
- Demonstrated that there is a low level of risk in developing the complete AEE

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Customers and Benefits

- Expected customers
  - Fuel cell/reformer developers
  - DOE
- Aid to fuel cell/reformer designers
  - Add their data and models
  - Link their analyses
  - Predict size, weight, performance of their designs
  - Provide vehicle implications
  - Assist in optimization of designs
  - Avoid blind alleys
- Identification of opportunities where high-impact improvements to subsystem/component technology (e.g. heat exchangers) will improve feasibility of advanced propulsion systems
- Improved prediction of effects of policy and component goals on total fleet through interaction with tech targets tool
- Extendable to other forms of advanced propulsion